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Thermally Assisted Current-Driven Dynamics in Asymmetric Spin Valves

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Current-induced steady precessional modes in standard spin valves are usually excited as an interplay of spin-transfer torque, Gilbert damping, and external magnetic field. We propose an asymmetric spin valve, in which the spin current can excite stationary precessional modes also at zero external magnetic field. We also show that finite temperature can induce transitions between different dynamical modes. These transitions, in turn, lead to telegraph noise in magnetoresistance.

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1. Introduction

Spin-polarized current passing through a ferromagnetic layer can transfer angular momentum from conduction electrons to magnetic moment of the layer [1]. The spin transfer can lead to the phenomenon of current-induced magnetic switching which has been extensively studied in the recent literature both theoretically and experimentally. Depending on the current and applied magnetic field, the spin-transfer torque in spin valves can either switch magnetic moment of the thin magnetic layer between different static states or excite a variety of steady-state dynamical modes. Magnetic excitations induced by spin-polarized current are intensively studied not only due to their interesting physical nature, but also due to potential application possibilities, e.g. for fast switching of nanoelements and design of nanosized dc-current-driven microwave generators. In typical spin-valve systems, the steady precessions have been observed for both external magnetic field and current density exceeding relevant critical values [2]. It has been shown recently that current-induced microwave oscillations in certain asymmetric spin-valves can occur without external field owing to a non-standard angular dependence of the spin torque [3]. In this paper we study temperature effects on the current-driven modes in asymmetric spin valves.

2. Description of the system

We consider the spin valve IrMn/Co(6)/Ru(2)/Co(4)/Cu(8)/Py(4)/Cu, where the numbers in parentheses are layer thicknesses in nanometers. The system is shown schematically in the inset to Fig. 1a and consists of pinned and reference cobalt layers (Co(6) and Co(4), respectively) separated by a ruthenium layer, copper spacer layer, and sensing permalloy layer. The parallel (P) and antiparallel (AP) configurations refer to the relative alignment of magnetic moments of the reference and sensing layers. Strong antiferromagnetic coupling is assumed between the Co layers across the Ru layer, which significantly reduces the dipolar field acting on the sensing layer. The Co layer pinned via exchange bias to the IrMn layer and the reference Co layer do not undergo dynamics in current densities of interest.

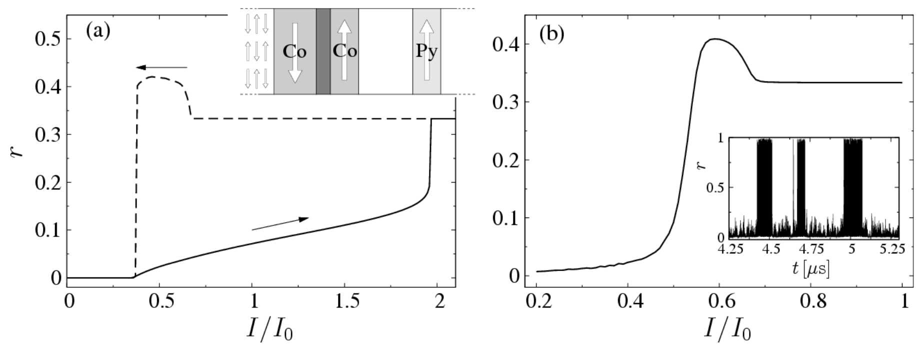

Fig. 1. Current driven magnetoresistance behavior (a) in zero temperature limit scanned with increasing (solid line) and decreasing (dashed line) current for the spin-valve shown schematically in the inset (parallel configuration), and (b) current dependence of the averaged magnetoresistace signal at room temperature. The inset in (b) shows the magnetoresistance telegraph noise for $I = 0.5 I_0$. The results were obtained for the sweeping current rate 1.2×10^4 A/(cm^2 s).

Magnetic dynamics of the sensing layer has been described by the Landau–Lifshitz–Gilbert equation, which contains standard precessional and damping torques and the torque $\boldsymbol{\tau}$ due to spin-transfer [4]. The precessional torque is proportional to the effective field which includes the uniaxial magnetic anisotropy field and the demagnetization field of a flat ellipsoid. The spin-transfer torque $\boldsymbol{\tau} = \boldsymbol{\tau}_\theta + \boldsymbol{\tau}_\varphi$, with $\boldsymbol{\tau}_\theta = aI\hat{\boldsymbol{s}} \times (\hat{\boldsymbol{s}} \times \hat{\boldsymbol{S}}) = \tau_\theta \hat{\boldsymbol{e}}_\theta$, and $\boldsymbol{\tau}_\varphi = bI\hat{\boldsymbol{s}} \times \hat{\boldsymbol{S}} = \tau_\varphi \hat{\boldsymbol{e}}_\varphi$. Here

$\hat{\boldsymbol{e}}_\theta$ and $\hat{\boldsymbol{e}}_\varphi$ are the unit vectors of a coordinate system associated with the polar θ and azimuthal φ angles describing orientation of the spin moment $\hat{\boldsymbol{s}}$ of the sensing layer relative to the spin moment $\hat{\boldsymbol{S}}$ of the reference layer. The current I is defined as positive when it flows from the sensing layer towards the reference one. The parameters a and b have been calculated in the diffusive transport regime [5].

3. Results and discussion

The parameter b is almost two orders of magnitude smaller than the parameter a, so the torque τ_φ plays a negligible role in the initial switching. The τ_θ acting on the Py sensing layer exhibits a non-standard angular dependence. It vanishes in collinear (P and AP) configurations, and additionally at a non-collinear configuration $\theta = \theta_{\rm c}$ [3]. Thus, for positive current both the collinear configurations are destabilized when current density exceeds the corresponding critical values, and the steady precessional regime can emerge.

In Fig. 1a we show the parameter $r = [1 - \cos^2(\theta/2)]/[1 + \cos^2(\theta/2)]$ as a function of the current density. The parameter r is basically used to describe magnetic configuration of the system and satisfactory approximates angular variation of magnetoresistance in symmetric valves. Therefore, we call r reduced magnetoresistance, although exact angular variation of the magnetoresistance in the asymmetric valve can be different. The arrows in Fig. 1a indicate direction of the current change. The P state is stable up to $I = 0.36 I_0$, where $I_0 = 10^8$ A/cm^2, and then the system is driven (with increasing I) to the in-plane oscillations. The fundamental frequency of the magnetoresistance oscillations decreases with increasing I. The in-plane regime is stable up to $I = 1.95 I_0$, where the system is switched to high-resistance static state. The non-zero τ_φ at $\theta \to \theta_{\rm c}$ assists in the transition to the static state and thus reduces the critical current for switching. The static states are stable up to a large current density and give rise to the current-driven hysteresis. When current is decreased, the out-of-plane oscillatory modes appear for $0.4 < I/I_0 < 0.6$. The fundamental frequency of the out-of-plane oscillations decreases with decreasing current. For the current densities close to $I = 0.5 I_0$ both the in-plane and out-of-plane modes have similar frequencies. However, both the regimes are well separated by irreversible paths, as follows from the presence of hysteresis.

Finite temperature leads to a finite probability for thermally activated switching, which may play a significant role, particularly in nanoscale systems. To study the temperature effects on spin valve behavior, we model the thermal fluctuations by adding a Langevin random field with Gaussian statistical properties to the effective field. The leading fluctuation term in the spin-transfer torque is however due to its dependence on the thermal magnetization fluctuations [6].

We have performed simulations of spin valve behavior at room temperature. The reduced magnetoresistance averaged over several hundreds of realizations, shown in Fig. 1b as a function of current, reveals vanishing hysteretic behavior.

The double peak structure in the power spectra for $0.4 < I/I_0 < 0.55$ indicates that the vanishing hysteresis is a result of "telegraph" jumps between the in-plane and out-of-plane regimes, see the inset to Fig. 1b. We have analyzed the bistability by accumulating the probability distribution function (pdf) of the dwell times $\tau_{\rm dw}$ for both the regimes. The exponential tails of pdfs are related to the Poisson process, where thermally induced hopping via the potential barrier and decay into the steady oscillatory regime take place at a rate described by the Arrhenius law, $\propto \exp(-E/k_{\rm B}T)$, where E is the energy barrier modified by the spin transfer. On the other hand, at short times the pdf is proportional to $\tau_{\rm dw}^{-3/2}$, which is related to over-barrier processes. The power-law dependence can be identified as pdf of the first-passage time of a Brownian particle attempting the barrier in double well potential. A simple model of Brownian particle in a double-well potential provides physical insight into the mechanism underlying the bistability. A nonzero temperature leads to a decrease in the effective barrier. The current, in turn, modifies asymmetry of the potential.

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